LO and Timing Requirements

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- Timing Requirements (pulsars)
- Clocks
- Coherence/Stability requirements
- Commercial freq standards
- Calibration issues
- General implementation issues
- Phase transfer

Introduction

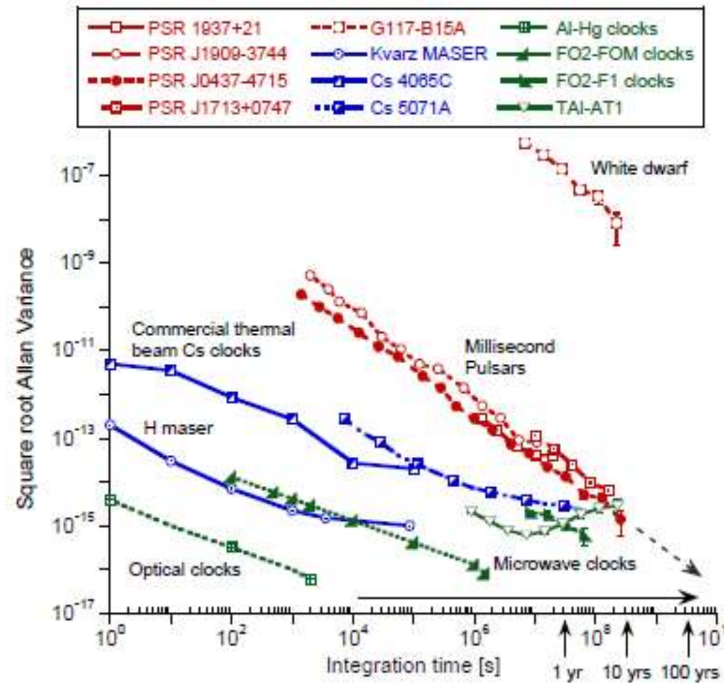
- Time & Frequency references are fundamental requirements for timing observations & interferometry
- Connected arrays already achieve phase transfer over 10-200km sufficient to maintain coherence for 20 GHz and above
- VLBI arrays use independent H-masers for observations >20 GHz; phase stable on timescales of minutes to hours at ~5 GHz
- Issues?
  - check requirements
  - review frequency standards, distribution techniques
  - phase calibration
  - manageable & cost-effective implementations for >1000 elements

Timing Requirements

Pulsar Timing

- few x 10ns now for best MSPs
- goal ~ 10ns SKA_1,
  ~few ns SKA_2 ?
- Time standard derived from local H-maser
- referenced through GPS ultimately to TT(BIPM)
  - long term stability
- Pulsar timescale?

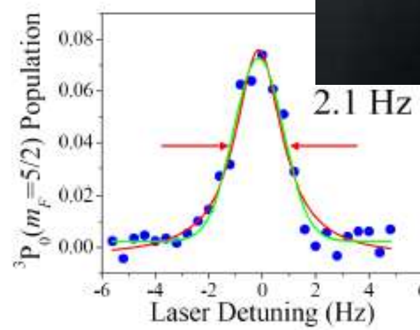
Requirements for timing fast transient events?



Hartnett & Luiten 2010

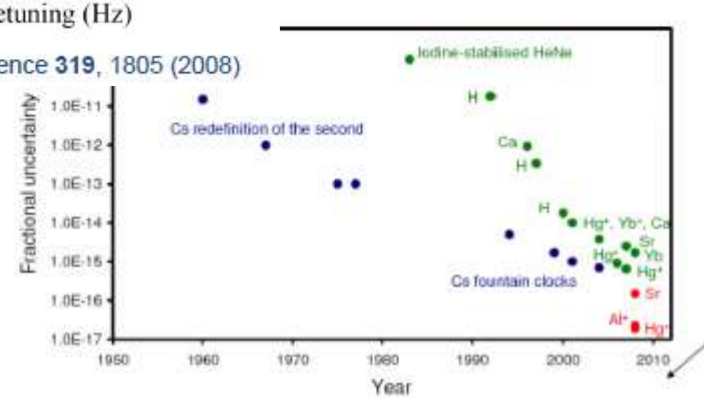
Optical clocks

- Trapped ion clocks now at 10^{-17}
- ESA have considered replacing H-masers with optical clocks at major ground stations (ESA/NPL report)
- ~ €1M cost + development
- Significant environmental issues (B-field, acceleration, acoustics)
- Should radio astronomers have similar ambition
- SKA ***could*** be location for significant frequency/time standard
  - links to other time standard labs
  - links to astro timescales
  - links to s/c navigation, gravity experiments



A. Ludlow et al. Science **319**, 1805 (2008)

$^2S_1$



Coherence (Stability) Requirements

$$C(T) = \left| \frac{1}{T} \int_0^T e^{j\phi(t)}\, dt \right|$$

- Coherence function C(T)

  Loss $<C^2(T)>$

  For Gaussian ϕ

  8 dg rms → 1% loss

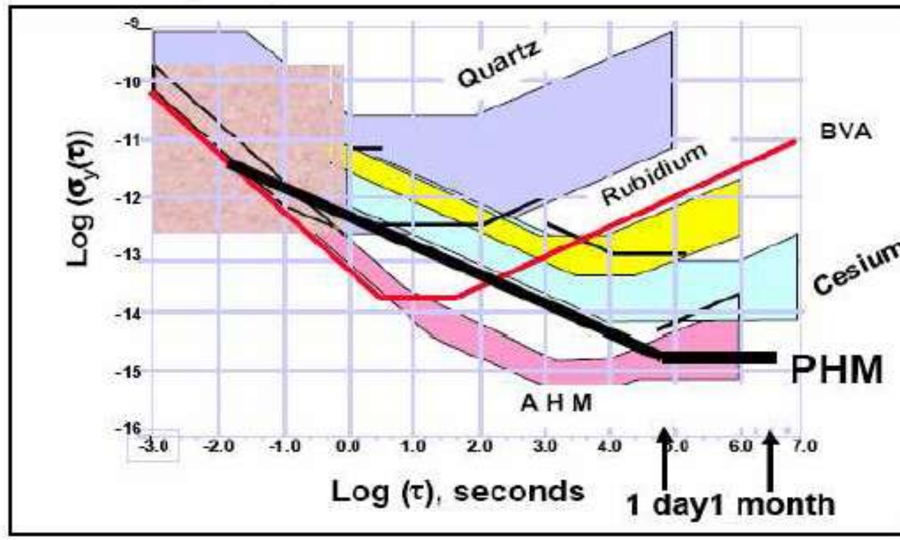
  2 ps at 10 GHz
- Clearly must achieve this at integration (~1s) level
- Longer timescale requirements depend on calibration approach

(Commercial) Oscillator performance

- At 1 sec best quartz oscillators (BVA) are very good!
- Active H-maser better > 10s
- At 1000s:

Passive H-maser : 10^{-14}

Active H-maser 10^{-15}



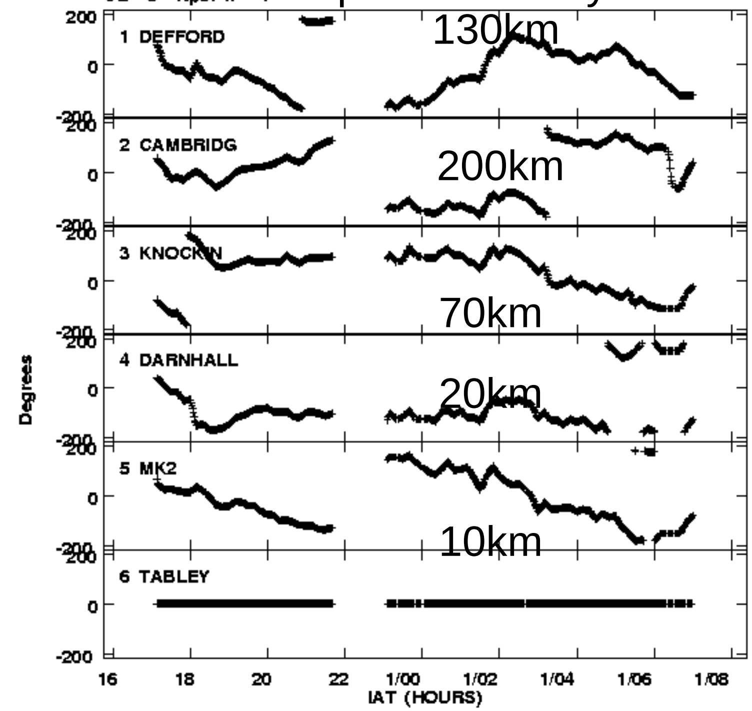
![PrepSKA Square Kilometre Array logo]

Stability requirements and calibration techniques

- Current cm-wavelength interferometers use phase referencing:
  - switch to (compact, bright) ref source
  - minimize angle (atmosphere, geometry); <5dg
  - minimize time (atmosphere); < 10 min
  - require linear phase drift over switching cycle
  - accustomed to stability
- Dynamic range ~ $n_a \, n_t^{1/2} / (\Delta\phi)$
  - VLA 1hr; MERLIN 12hr

    $\Delta\phi$ 10dg → DR ~ 400:1
  - SKA_1 1500:1

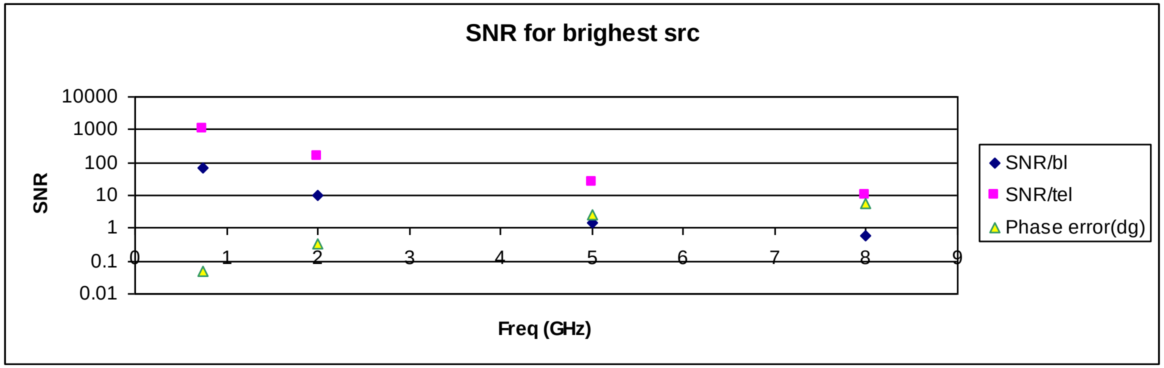
MERLIN: phase stability over 16h



SKA$_1$ Calibration

- 0.5 - 10 GHz (b/w 0.5..1..2...4 GHz)
- Tsys = 30;
- 250 x 15m dishes
- t_{int}=100s
- SNR/bl on expected brightest source in FOV
- Per tel Phase error
  ~8 dg at 8 GHz
- Based on 1.4 GHz source counts
- For 200km baselines; ~30% sources unresolved (Garrington & Garrett, Gurvits et al); stations helps
- But t_{int}=10s difficult
- Require 100-1000s stability for >5 GHz

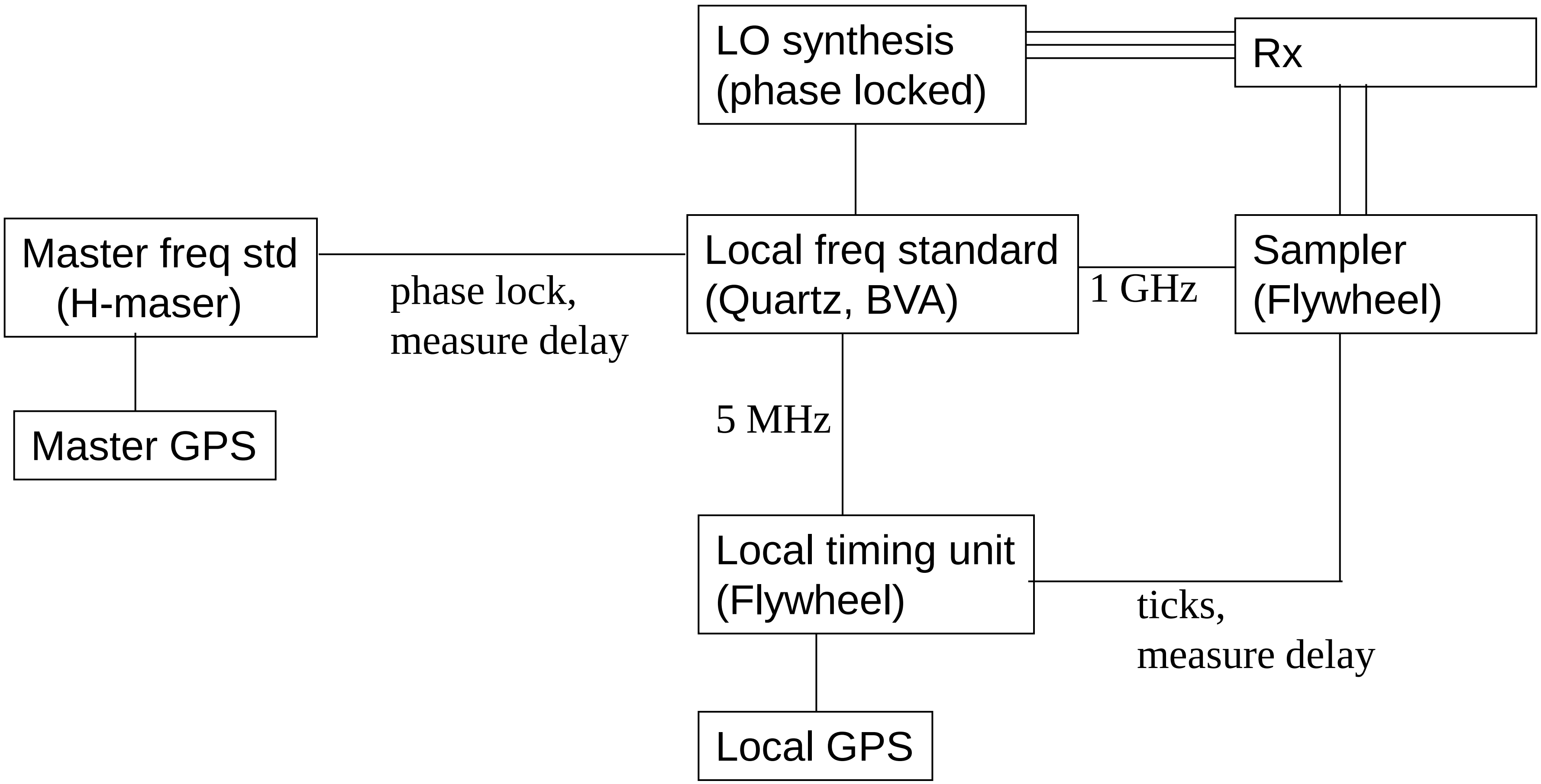
(Could manage with 10-100s < 5 GHz)



Requirements and general implementation issues

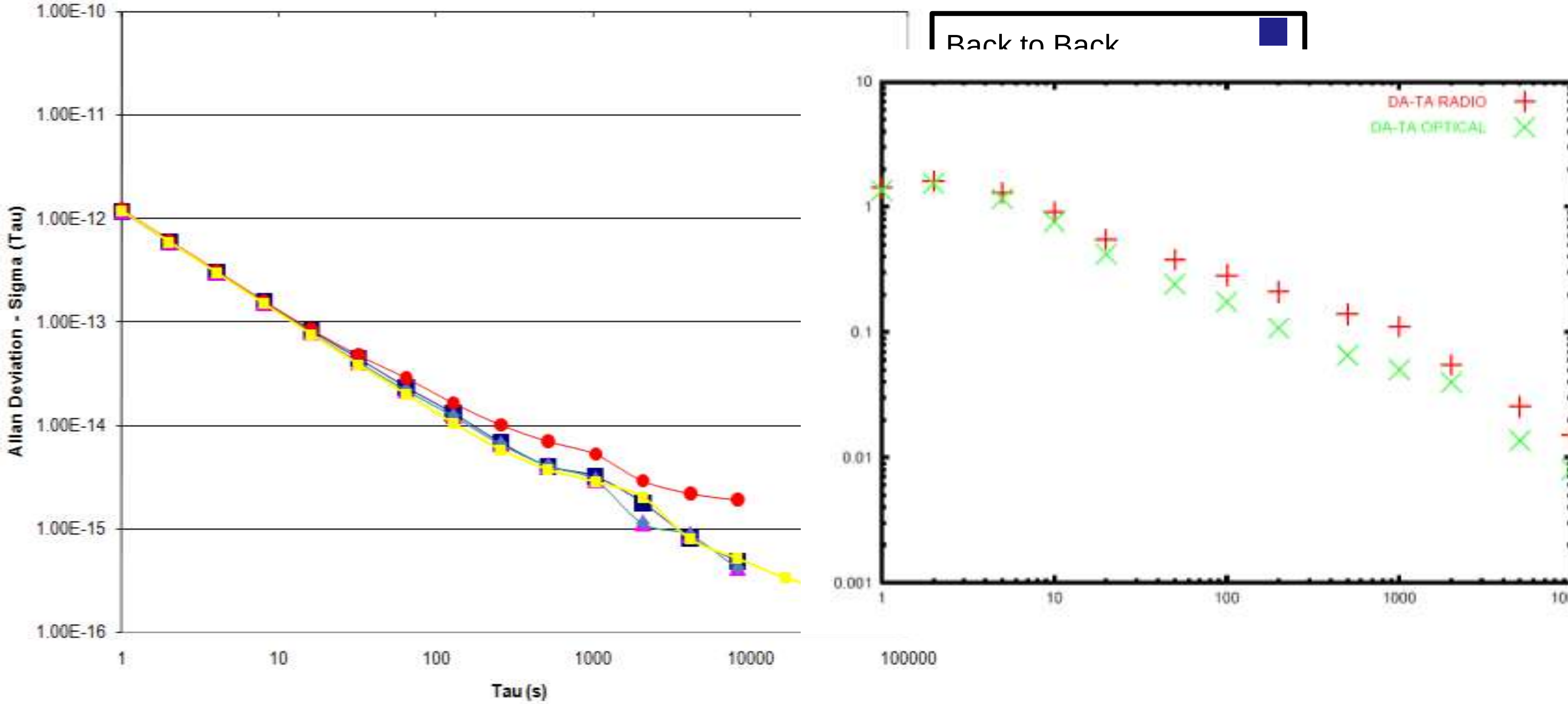
- Rb, Quartz (BVA), PHM probably not good enough
  - insufficient stability on 100-1000s
- Need H-maser(s) + distribution system
  - take advantage of short term stability of BVA at remote site
- Dishes/stations need to derive LOs, sampler clocks, 1pps from local station oscillator (BVA)
  - trace 1pps to UTC via GPS
  - phase-locked multipliers for LOs

Time & Freq system



Phase transfer systems

- ~1-2ps over 1s-10min demonstrated in SKADS



- Most distant stations could use independent clocks

Time and Frequency processing at dish/station

- Requirements
  - reference 1 pps ticks coherent (jitter < 0.1 ns) with central clock LO maser.
  - measure 1pps against local GPS ticks ~10ps
  - provide optical timecode as required (cf WIDAR correlator TC)
  - measure the round trip delay to sampler
  - provide tick-timing offsets to the correlator/data acquisition system for corrections in software

Time & Freq Processing at dish/station

- e-MERLIN Implementation (B Anderson et al)

  low cost iLotus (ex Motorola) GPS: 2-3 ns stability

  5/10 MHz input (maser/crystal)

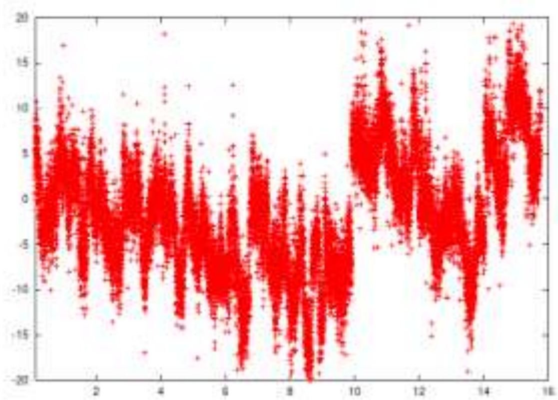
  Clock synthesis chip: 128 & 512 MHz

  FPGA: Flywheel divider chain by 2048, 625, 5 and 20 generates the 1 second ticks from the 128 MHz

  Divide by 625, 5 and 20 are cleared by the 1 second ticks from the GPS receivers

  The GPS ticks and the incoming TCs sample the divide by 2048 to measure coarse delay (8ns)

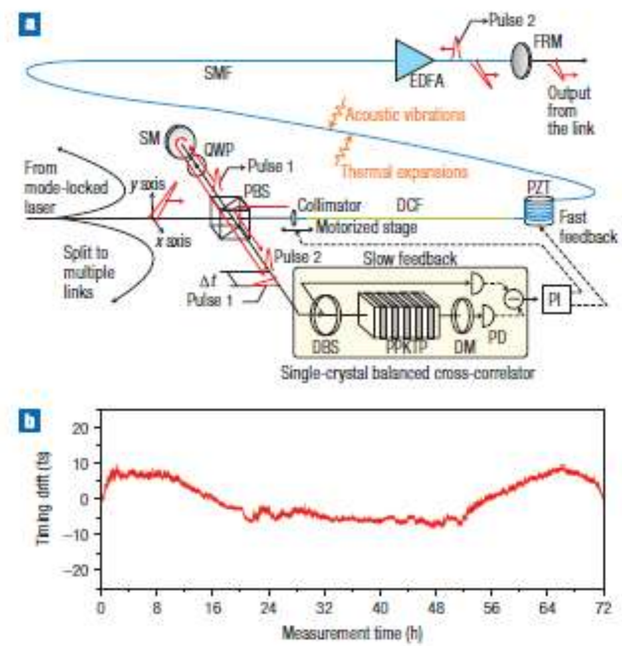
  Fine delays (0.5 ns) are obtained by processing multiple copies of offset ticks.



s/w correction can improve to <5ns

Femtosecond time distribution

- X-ray Free Electron lasers use fs pulses; require fs synchronisation of major, distributed subsystems
- Use mode-locked lasers & active compensation on fibre links; 6 fs rms over 72 hrs/300m
- Techniques for locking 10 GHz reference with stability 2 x 10^-19
- Will be developed for facility use, across range of applications



Kim et al 2008

Work Plan

- Requirements
  - improved calibration analysis using sky and system simulation
  - other timing requirements (transients)
  - low frequency requirements (LOFAR)
  - formalise for system design
- Review
  - facility-class optical clocks; time transfer techniques
- Inputs from Pathfinders/Precursors
  - e-MERLIN, EVLA: Phase transfer on fibre
  - e-MERLIN: local GPS clocks
  - LOFAR: Rb
  - MeerKAT: fibre phase studies
- Phase transfer
  - design for low-cost, scalable, reliable pulse distribution system
  - performance evaluation

Conclusions

- Timing requirements for pulsars: 10ns
- Case for next-generation (optical) clock
- Interferometry requirements
  - 8dg @ 10 GHz (2 ps)
  - stability over 100-1000s
  - used to stability over many hours
  - → active H-maser + distribution system
- Architecture
  - central freq std & clock → phase transfer → local standard referred to local GPS
- Phase transfer
  - ps stability over 1-1000s demonstrated using pulse transmission on fibre over 100km, multiple hops; working on scalability
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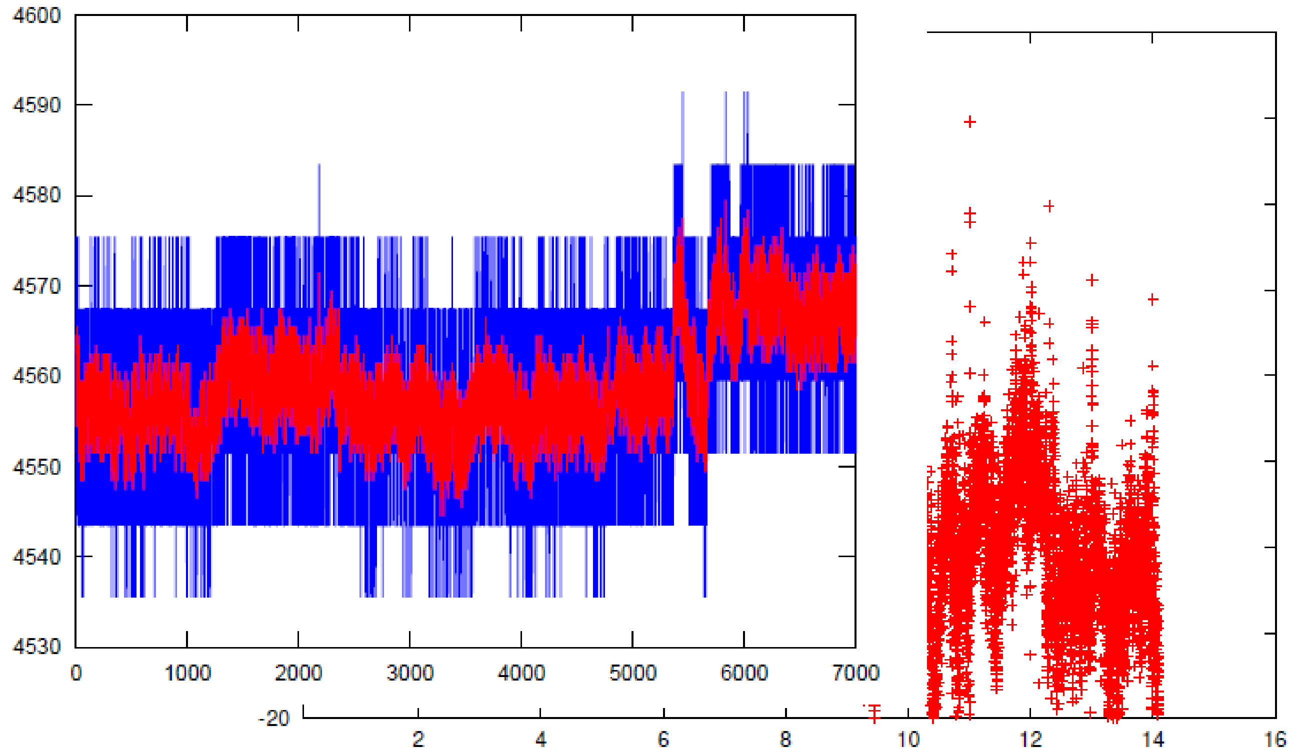
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